EXHIBIT C

Designation: B 646 – 94

Standard Practice for Fracture Toughness Testing of Aluminum Alloys[1]

This standard is issued under the fixed designation B 646; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This practice has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

INTRODUCTION

Fracture toughness is a key property for a number of aluminum alloys utilized in aerospace and process industries, but at the current stage of development of fracture test techniques no standard methods exist to cover a number of the product lines or dimensional ranges involved. Plane-strain fracture toughness, K_{Ic}, is a keystone of the industry, but for the very tough alloys of principal interest, valid measurements can be made only for relatively thick sections. Thus it is necessary to provide this standard practice for uniform quality control test procedures for the industry, pointing out which current standards are utilized in specific cases, and providing guidelines where no standards exist.

1. Scope*

1.1 This practice provides guidance for testing (*a*) thin products, of thicknesses equivalent to sheet that is, (≤0.249 in. (6.30 mm)), (*b*) intermediate thicknesses of plate, forgings, and extrusions, too thin for valid plane-strain fracture toughness testing but too thick for treatment as sheet, that is over 0.249 in. (6.30 mm) and up to 1 to 2 in. (25 to 50 mm), dependent upon toughness level, and (*c*) relatively thick products where Test Method E 399 is applicable. For changes to this specification since the last issue, refer to the Summary of Changes section at the end of the standard.

1.2 This practice addresses the problem of screening tests, recognizing the complexity and expense of making formal fracture toughness measurements on great quantities of production lots, and provides alternatives in the form of simpler, less expensive tests that may be carried out either in a research or production test laboratory.

1.3 The values stated in inch-pound units are to be regarded as the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

B 557 Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products[2]

B 645 Practice for Plane Strain Fracture Toughness Testing of Aluminum Alloys[2]

E 23 Test Methods for Notched Bar Impact Testing of Metallic Materials[3]

E 338 Test Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials[3]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]

E 561 Practice for *R*-Curve Determination[3]

E 602 Test Method for Sharp-Notch Tension Testing with Cylindrical Specimens[3]

E 616 Terminology Relating to Fracture Testing[3]

E 1304 Test Method for Plane-Strain (Chevron Notch) Fracture Toughness of Metallic Materials[3]

2.2 *Other Document:*

Aluminum Association Bulletin T5, "Fracture Toughness Testing of Aluminum Alloys"[4]

3. Terminology

3.1 The terminology and definitions in the referenced documents are applicable to this practice.

3.2 *Descriptions of Terms Specific to This Standard:*

3.2.1 For purposes of this practice, the following descriptions of terms are applicable in conjunction with Practice E 561 and use of the compact specimen:

3.2.1.1 $K_{R_{25}}$—A value of K on the R-curve based on a 25 % secant intercept of the load-crack opening displacement test record and the effective crack length at that point that otherwise satisfies the remaining-ligament criterion of Practice E 561.

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[1] This practice is under the jurisdiction of ASTM Committee B-7 on Light Metals and Alloys, and is the direct responsibility of Subcommittee B07.05 on Testing.

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[2] *Annual Book of ASTM Standards*, Vol 02.02.

[3] *Annual Book of ASTM Standards*, Vol 03.01.

[4] Available from The Aluminum Association, 750 3rd Ave., New York, NY 10017.

* A Summary of Changes section appears at the end of this practice.

3.2.1.2 $K_{R_{max}}$—A value of K on the R-curve based on the maximum load value of the load-crack opening displacement test record and the effective crack length at that point that otherwise satisfies the remaining-ligament criterion of Practice E 561. The $K_{R_{max}}$ value is used when the 25 % secant intercept occurs at a point after the maximum load is reached.

3.2.2 For purposes of this practice, the following descriptions of terms are applicable in conjunction with the chevron notch (short-rod and short-bar) Test Method E 1304.

4. Summary of Practice

4.1 This practice provides guidelines for the selection of tests for the evaluation of the fracture toughness properties of aluminum alloys, particularly for quality assurance and material release purposes, including:

4.1.1 Center-slotted panel testing of sheet products in accordance with Practice E 561, M(T) specimen procedures.

4.1.2 Screening tests of sheet products in accordance with Test Method E 338.

4.1.3 Plane-strain fracture toughness tests in accordance with Test Method E 399.

4.1.4 Intermediate thickness fracture toughness tests in accordance with Practice B 645 and Test Method E 399.

4.1.5 Intermediate thickness fracture toughness tests in accordance with Practice E 561 using the C(T) (compact specimen) and a 25 % secant-intercept value concept, designated as $K_{R_{25}}$, as a single value or discrete point evaluation of the crack-growth resistance curve (R-curve).

4.1.6 Screening tests of both intermediate and relatively thick materials using the chevron notch (short-rod or short-bar) Test Method E 1304.

4.1.7 Screening tests for a range of thickness from about 0.1-in. (2.54 mm) upward using the sharp notch Charpy test as covered in Test Methods E 23.

4.1.8 Screening tests of thick materials in accordance with Test Method E 602.

5. Significance and Use

5.1 This practice is provided to develop and maintain uniformity in practices for the evaluation of the toughness of aluminum alloys, particularly with regard to quality assurance and material release to specifications.

5.2 It is emphasized that the use of these procedures will not alter the validity of data determined with specific test methods, but provides guidance in the interpretation of test results (valid or invalid) and guidance in the selection of a reasonable test procedure in those instances where no standard exists today.

6. Selection of Test Procedures

6.1 The following methods are recommended for individual products and situations:

6.1.1 For products in sheet thicknesses, that is nominally ≤0.249 in. (6.30 mm), the measurement of critical stress intensity factor (Kc) associated with a monotonically loaded center-slotted panel tested in general accordance with Practice E 561 for center-cracked tension (M(T)) specimens is recommended, as described in 7.2.

6.1.2 For products in sheet thicknesses, the use of tension tests of sharply edge-notched specimens in accordance with Test Method E 338, and the corresponding correlations of such data with the critical stress-intensity factors from tests of center-slotted panels in accordance with Practice E 561, as modified by this practice, are recommended for screening and quality control purposes as described in 7.3. The sharp notch Charpy screening test in accordance with Test Methods E 23 may also be applied for correlative purposes.

6.1.3 For relatively thick high-strength products, plane-strain fracture toughness tests in accordance with Test Method E 399 as supplemented by Practice B 645 are recommended. For further guidelines, refer to Practice B 645; no further description is covered herein.

6.1.4 For screening tests of relatively thick high-strength products, tension tests of sharply notched cylindrical specimens and the associated correlations with plane-strain fracture toughness as determined in accordance with Test Method E 399 and are recommended, as described in 8.2.2. Additional alternative screening tests that are recommended for relatively thick products are the chevron notch (short-rod and short-bar) test described in Test Method E 1304 and 8.2.1 and the sharp notch Charpy screening test in accordance with Test Methods E 23 and 8.2.3.

6.1.5 For intermediate thicknesses of high-strength products, too thin for valid plane-strain fracture toughness testing but too thick for large panel testing in accordance with Practice E 561, a modification of compact specimen testing in accordance with Test Method E 399 as described in Practice B 645 and Section 9 is recommended. For such intermediate thickness products, three additional alternative tests exist. They are as follows: a direct measure of fracture toughness using Practice E 561 and the $K_{R_{25}}$ concept as described in 9.2.1.1, the same screening tests suggested for thick products involving the chevron notch (short-rod or short-bar) test as described in Test Method E 1304 and 8.2.1 and the sharp notch Charpy test in accordance with Test Methods E 23 and 8.2.3.

6.2 It is pointed out that there are no current standard recommendations for toughness testing of relatively low-strength aluminum alloys which display large-scale yielding even in the presence of extremely large cracks in very thick sections. Such cases must be dealt with individually on a research basis using tests selected from program needs and anticipated design criteria. A typical case for general guidance is given in the literature.[5]

7. Fracture Toughness of Thin Sections

7.1 If a complete and precise measure of the fracture toughness of sheet or of sections of an extruded, welded, or forged shape equal to or less than 0.249 in. (6.30 mm) in thickness is required, the crack-resistance curve should be measured in accordance with Practice E 561.

7.2 For quality assurance or material release purposes, the critical (or maximum) stress intensity factor for monotonically loaded M(T) panels tested in general accordance with Practice E 561 is recommended as the index of fracture toughness. This value is designated K_c for purposes of this practice.

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[5] Kaufman, J. G., and Kelsey, R. A., "Fracture Toughness and Fatigue Properties of 5083-0 Plate and 5183 Welds for Liquefied Natural Gas Applications," *Properties of Materials for Liquefied Natural Gas Tankage, ASTM STP 579*, ASTM, 1975, pp. 138–158.

7.2.1 The recommended specimen size is 16 in. (405 mm) wide with 15 in. (380 mm) being an acceptable minimum width. The initial crack length, a, should be equal to one quarter of the width, W; that is, $a/W = 0.25$. The center-slot length may be either fatigue-cracked or machine-notched, as long as the ends of any machined slot are sharpened with a jeweler's saw or sharp notching tool.

7.2.2 Specimen widths less than 15 (381 mm) may be used for quality assurance or lot release testing, but it must be recognized that the maximum or critical stress intensity factor is dependent upon the interaction of the crack-driving force, a function of specimen width, and the crack-resistance curve, so the value is specimen width (as well as thickness) dependent. The value will decrease with decreasing specimen width, all other factors being identical.

7.2.3 Except when specifically stated, tests to measure K_c with such specimens shall be made with face stiffeners to prevent buckling above or below the center slot.

7.2.4 The K_c value will be calculated at the maximum load by the use of the secant or polynomial equation for M(T) panels given in Practice E 561. If, as sometimes happens, there is considerable crack extension at maximum load, the point at which the load first reaches the maximum shall be used in the crack length calculations.

7.2.5 Values of K_c calculated under conditions in which the net section stress exceeds 80 % of the tensile yield strength of the material are not suitable for design purposes and do not express the full toughness capability of the material, but they are useful for quality control or lot release; and such value of K_c that equals or exceeds a specified minimum value shall constitute evidence that the material passes the stated specification if the latter is based upon tests of the same or a larger width of specimen.

7.3 In cases where the use of screening tests is desired, the double-edge notched sheet-type specimen in Fig. 3 of Test Method E 338 or the sharp notch Charpy specimen in Fig. 4 of Test Methods E 23 is recommended, and those methods should be used in making the tests. The ratio of sharp-notch strength to tensile yield strength or the Charpy energy has been shown to correlate reasonably with K_c from 16 in. (405 mm) wide center-slotted panels and, if a suitable correlation has been established for the alloy/temper/product in question, the ratio may be used as a lot release criterion. Additional background and guidance on such use is presented in Section 10.

8. Fracture Toughness of Thick Sections

8.1 For thick sections of high-strength alloys, plane-strain fracture toughness, K_{Ic}, as determined by Test Method E 399, is the standard, as supplemented by Practice B 645.

8.2 Where screening tests are desired, any one of the following three different type tests may be used: the chevron notch (short-rod or short-bar) specimen tested in accordance with Test Method E 1304. The sharp cylindrically notched tension specimen tested in accordance with Test Method E 602 and the sharp notch Charpy test with root radius <0.001-in. (0.0254 mm) tested in accordance with Test Methods E 23.

8.2.1 Chevron notch (short-rod or short-bar) specimens.

8.2.1.1 Standard chevron notch (short-rod or short-bar) specimens 1.00-in. (25.4-mm) in diameter or 1.00-in. (25.4-mm) wide are recommended.

8.2.1.2 Use of the Chevron notch (short-rod or short-bar) specimen test method is strongly recommended for screening purposes. This test can be a direct measure of K_{I_c} and as a replacement or an alternative to Test Method E 399. Two relatively attractive features of the chevron notch (short-rod or short-bar) method are fatigue precracking is not required and small overall test volume.

8.2.1.3 The stress intensity value, K_{IvM}, determined in accordance with Test Method E 399, Annex 1, has been shown to correlate reasonably well with plane-strain fracture toughness, and if a suitable correlation has been established for the alloy/temper/product in question, the value may be used as a lot release criterion. Additional background and guidance on such use is presented in Section 10 and in the literature.[6]

8.2.2 Sharp cylindrically notched tension specimen:

8.2.2.1 While both standard specimens, ½ in. (12.5 mm) and 1¹⁄₁₆ in. (27 mm) in diameters, are used for quality control testing, the 1¹⁄₁₆-in. (27-mm) specimen is generally more cost effective particularly for very tough alloys and tempers, because of the greater sensitivity to differences in fracture toughness at high toughness levels.

8.2.2.2 The ratio of sharp-notch strength to tensile yield strength has been shown to correlate reasonably well with plane-strain fracture toughness, and if a suitable correlation has been established for the alloy/temper/product in question, the ratio may be used as a lot release criterion. Additional background and guidance on such use is presented in Section 10 and the literature.[7]

8.2.3 *Sharp Notch Charpy Specimens:*

8.2.3.1 Charpy impact tests have long been employed as a measure of toughness of metals and have been used to predict the plane strain fracture toughness. Various types of notches have been used including a precrack, but a sharp notch is considerably more cost effective.

9. Fracture Toughness of Intermediate Sections

9.1 For alloy, temper and product combinations greater than 0.249 in. (6.30 mm) in thickness but thinner than that sufficient to satisfy the thickness criterion for plane-strain conditions, the fracture toughness shall be determined in accordance with Test Method E 399 as supplemented by Practices B 645 or E 561, utilizing the $K_{R_{25}}$ concept with the compact specimen.

9.1.1 Test Method E 399 as supplemented by Practice B 645..

9.1.1.1 The lot shall be considered to meet or exceed the requirements of the specification if all the validity requirements of the test listed in 9.1 and 9.1.1 are met except for thickness and the values of K_Q exceed the values specified for K_{I_c}.

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[6] Bray, J. W., "Use of Chevron Notch Short Bar Test to Guarantee Fracture Toughness for Lot-Release in Aluminum Alloys," *Chevron-Notch Fracture Test Experience: Metals and Non-Metals, ASTM STP 1172*, ASTM, 1992, pp. 131–143.

[7] Jones, M. H., et al., "Sharply Notched Cylindrical Tension Specimen for Screening Plane-Strain Fracture Toughness," *Developments in Fracture Mechanics Test Methods Standardization. ASTM STP 632*, ASTM, 1977, pp. 115–152.

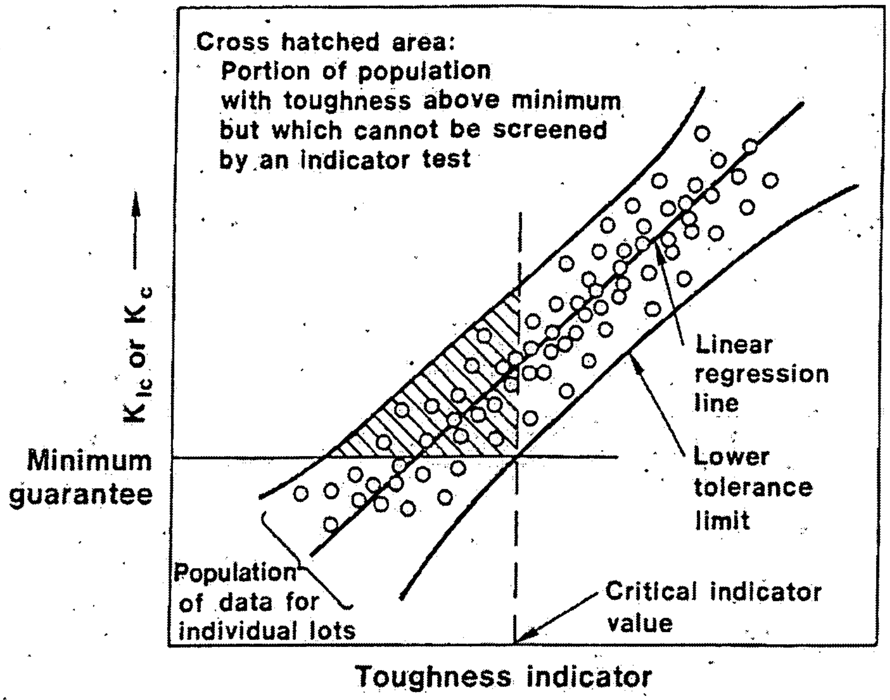

FIG. 1 Typical Toughness versus Toughness Indicator Relationship

9.2 Practice E 561 utilizing the $K_{R_{25}}$ concept with the compact specimen.

9.2.1 This method employs the compact specimen and Practice E 561. The recommended specimen geometry for the compact specimen is dependent on the strength, toughness, and thickness of the material. An evaluation of the material being tested for lot release should be made to determine the optimum specimen geometry; that is, at what point will the test yield a valid result in general accordance with Practice E 561. Once the specimen geometry is established, all future tests must be made utilizing the same specimen geometry.

9.2.2 In the event that a valid $K_{R_{25}}$ value (one satisfying the general requirements stated in Practice E 561) is not obtained and specimen buckling is not involved, the $K_{R_{25}}$ value obtained may still be useful as a qualitative result for general correlation purposes. Also, if the reason for invalidity is the critical remaining ligament criterion and the $K_{R_{25}}$ value exceeds the applicable specification values based upon tests of specimens of the same geometry for material of the same thickness, the result shall be considered as evidence that the lot meets the requirements of the specification.

9.3 For this class of materials, there are insufficient data to justify strong recommendations for screening test procedures. Presumably correlation with K_{I_c} test data could be made with the results of tests using either chevron-notch (short rod or short bar) specimens, or sharp-edge notched sheet-type specimens, circumferentially notched cylindrical specimens or sharp notch Charpy specimens.

10. Screening Tests

10.1 Because tension tests of M(T) panels and K_{Ic} tests are complex and expensive and require judgment in interpretation of results, they are not preferred for high-volume, plant quality control testing.

10.2 The more recently developed $K_{R_{25}}$ test method concept for testing intermediate thickness material and the chevron notch (short-rod or short-bar) screening test methods are less complex, much less expensive and may be better suited for high volume testing for quality control or lot release purposes, or both. These two approaches also provide results that can be used in a strictly qualitative manner as an ordinary screening test, and also hold the promise for direct quantitative measurement of fracture toughness[8] if all appropriate criteria of Test Method E 399 and Practice E 561 are satisfied.

10.3 Notch tension and sharp notch Charpy impact tests provide a relatively simple, inexpensive procedure and freedom from judgmental interpretation, and thus are used whenever possible for day-to-day in-plant production lot surveillance.[7]

10.3.1 The notch yield ratio, NYR, (ratio of sharp-notch strength to tensile yield strength) and sharp notch Charpy impact energies are generally a good indicator of relative fracture toughness, and may be used in correlation with K_c or K_{Ic} to develop lot release criteria.

10.3.2 Notched tension and sharp notch Charpy impact specimens used for the quality control of fracture toughness should be centered at the same level through the thickness of the section as would the center-cracked tension panel or plane-strain fracture toughness specimen for which they are being substituted.

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[8] Rolfe, S. T. and Novak, S. R. "Review of Developments in Plane-Strain Fracture Toughness Testing," *ASTM STP 463*, ASTM, Sept. 1970, pp. 124–159.

10.3.3 Ideally, tensile yield strengths used for validating K_{Ic} measurements or calculating notch-yield ratio values should be determined from specimens whose center lines are at the same level in the plate thickness as the center of the fracture toughness specimen. In general, this will not coincide with the requirements for tension specimen location in Methods B 557. To avoid confusion resulting from two sets of tensile properties, the yield strength from the specimen used to show conformance with tensile requirements (Methods B 557) should be used in the fracture toughness calculations.

10.4 Screening tests for lot release based on the correlation between chevron notch (short-rod or short-bar) values, notch-yield ratios or sharp notch Charpy values and equivalent values of K_c or K_{I_c} always have a region of uncertainty, as illustrated in Fig. 1. Screening test values in this region are not suitable for use as acceptance/rejection criteria. In this case, testing with the primary specimens (in accordance with Practices E 399 or E 561) is required for lot release purposes.

10.5 In the case of the compact specimen referred to in 6.1.5, the method involves selecting discrete points on the load versus crack opening curve and using the proper compliance equation to determine an effective crack length. It has been found that a 25 % secant or maximum load secant (whichever gives the smaller offset angle) provides a discriminatory value ($K_{R_{25}}$ or $K_{R_{max}}$) of fracture toughness.

10.5.1 To reduce the variables associated with the K method applied as a screening test, the following guidelines should be observed: choose a convenient compact specimen size that is near the required ligament length for a valid test without the necessity for absolutely meeting it and the crack length should be held essentially constant.

10.6 In conducting sharp notch Charpy impact tests, a low capacity impact machine of approximately 25 ft. lb (33.9 N·m) is recommended with sufficient sensitivity to measure preferably to the nearest 0.01 ft. lb (.014 N·m). Machining and maintaining the sharp notch may be most conveniently accomplished on a fly cutter with a single point carbide tool ground to a sharp point.

SUMMARY OF CHANGES

This section identifies the location of principle changes to this standard that have been incorporated since its last issue.

(1) 2.1—Added reference to E 1304.

(2) 3.2.2, 4.1.6—Replaced "method now under development by Task Group E24.01.04" with "Test Method E 1304." The test method has been developed and is now published as E 1304.

(3) 3.2.2.1—Deleted this paragraph. This definition is now given in E 1304.

(4) 3.2.2.2—Deleted this paragraph. There is no use or reference in the text of this practice to P_{MAX}.

(5) 4.1.1—Changed "CCT" to "M(T)." This is current notation for center-cracked tension panel.

(6) 4.1.5—Added "C(T)" as current notation and put compact specimen in parentheses.

(7) 6.1.1—Changed "(CCT)" to "(M(T))" as current notation.

(8) 6.1.4, 6.1.5—Added Test Method E 1304 as a reference in addition to 8.2.1.

(9) 7.2—Deleted "center-slotted" and replaced with "M(T)."

(10) 7.2.1—Changed the first sentence to include widths.

(11) 7.2.2—Deleted "or 16 in." and "or 406.4 mm" as not necessary to meaning or intent of this practice.

(12) 7.2.4—Changed "center-cracked" to "M(T)."

(13) 7.3, 8.2.2.2—Added "/product" after "alloy/temper." Correlations developed will also depend on the product form being tested.

(14) 8.2—Deleted the word "test" after "(short-rod or short-bar)" and added "specimen tested in accordance with Test Method E 1304." Also added "tested" after the values in same sentence for clarity.

(15) 8.2.1.2—Changed to "can be" in second sentence to make current.

(16) 8.2.1.3—Added this paragraph to Section 8 to recognize work results of Test Method E 1304.

(17) Added new footnote 6 to support Paragraph 8.2.1.3 and renumbered subsequent footnotes.

(18) 10.1—Changed "center-slotted" to "M(T)."

(19) 10.3.2—Changed "center-slotted" to "center-cracked tension."

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